Cryogenic Motion Control

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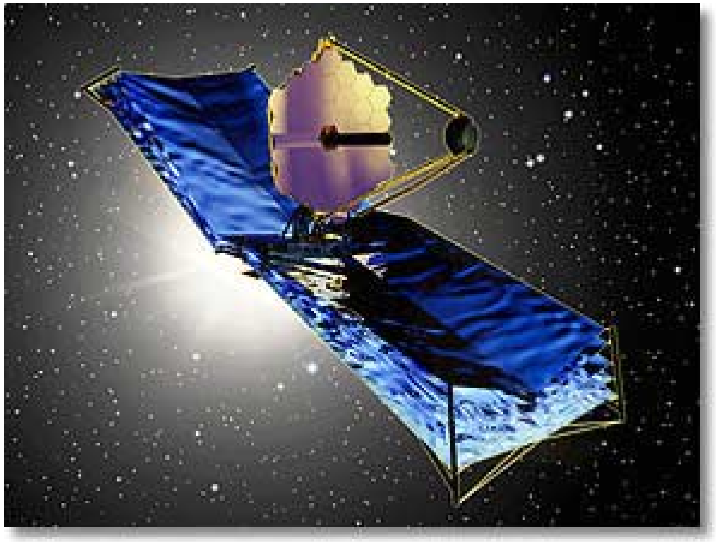
Definition

- Actuator –transforms energy into a limited range of motion
  - Linear
  - Rotary
  - Active device (uses power)

Applications

- Restraint, release and deployment
- Positioning
- Steering, pointing



Requirements

- Operating life
- Power
- Pointing accuracy
- Slew/scan rate
- Operating speed
- Deployment time
- Retractibility

Systemic Constraints

- Weight: negligible
- Stiffness: infinite
- Power: zero
- Envelope: miniscule
- Temp range: 0 – MP
- Vacuum compatible
- Outgassing: none
- Shock and vibration

Does not exist!

Types of Actuators

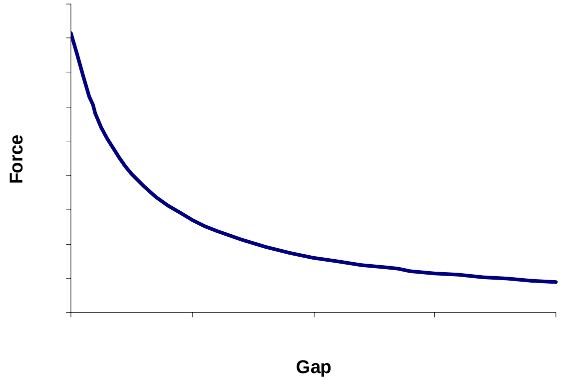
- Electromagnetic
  - Solenoid
  - Voice Coil
  - Motors
- Electrostatic
- Smart Materials
  - Piezoelectric
  - Magnetostrictive
  - Shape Memory
  - FSMA

The Central Challenge

- Prevent freeze up
- Ensure smooth operation
- Relative motion
  - Sliding
  - Rolling
  - Flexing

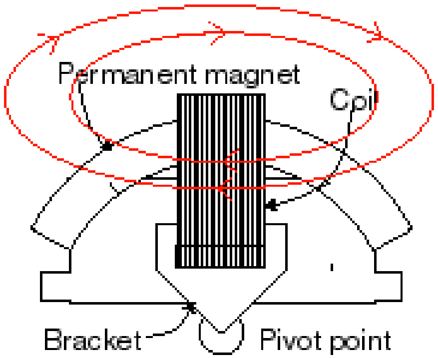
Electromagnetic - Solenoids

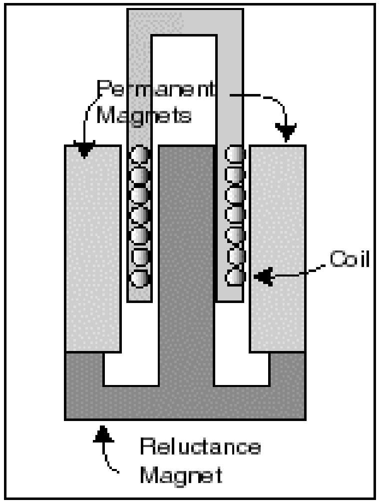
- Pull only
- Force inverse with gap
- Power required to maintain force



Electromagnetic - Voice Coils

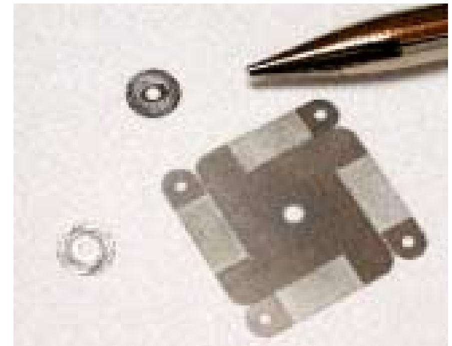
- Constant force devices
  - I x B
- Permanent magnets
- Force independent of position

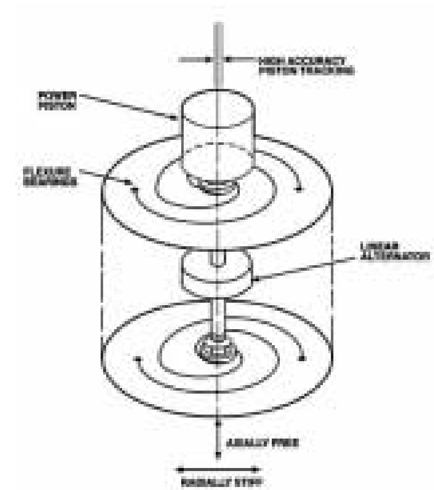




Flexures

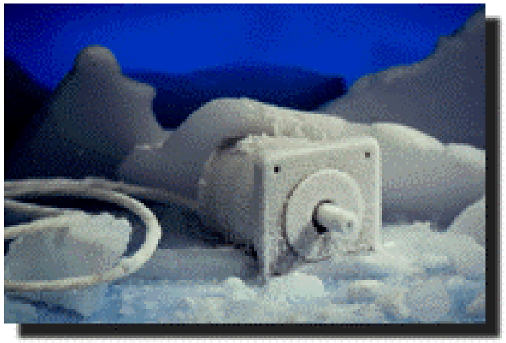
- Springs with high lateral stiffness
- Low friction
- Low stiction
- Eliminate hysteresis in mechanical joint





Types of motors

Direct current		Alternating Current	
Continuous	**Incremental**	**Single Phase**	**Polyphase**
Wound field: series, shunt, compound wound	Stepper motors: PM, variable reluctance	Induction: split phase, Capacitor start, Capacitor run Shaded pole Repulsion start	Induction: squirrel cage, wound rotor
Permanent magnet: PM torque, printed circuits, ironless Brushless w/ and w/o iron		Synchronous: hysteresis, reluctance	Synchronous



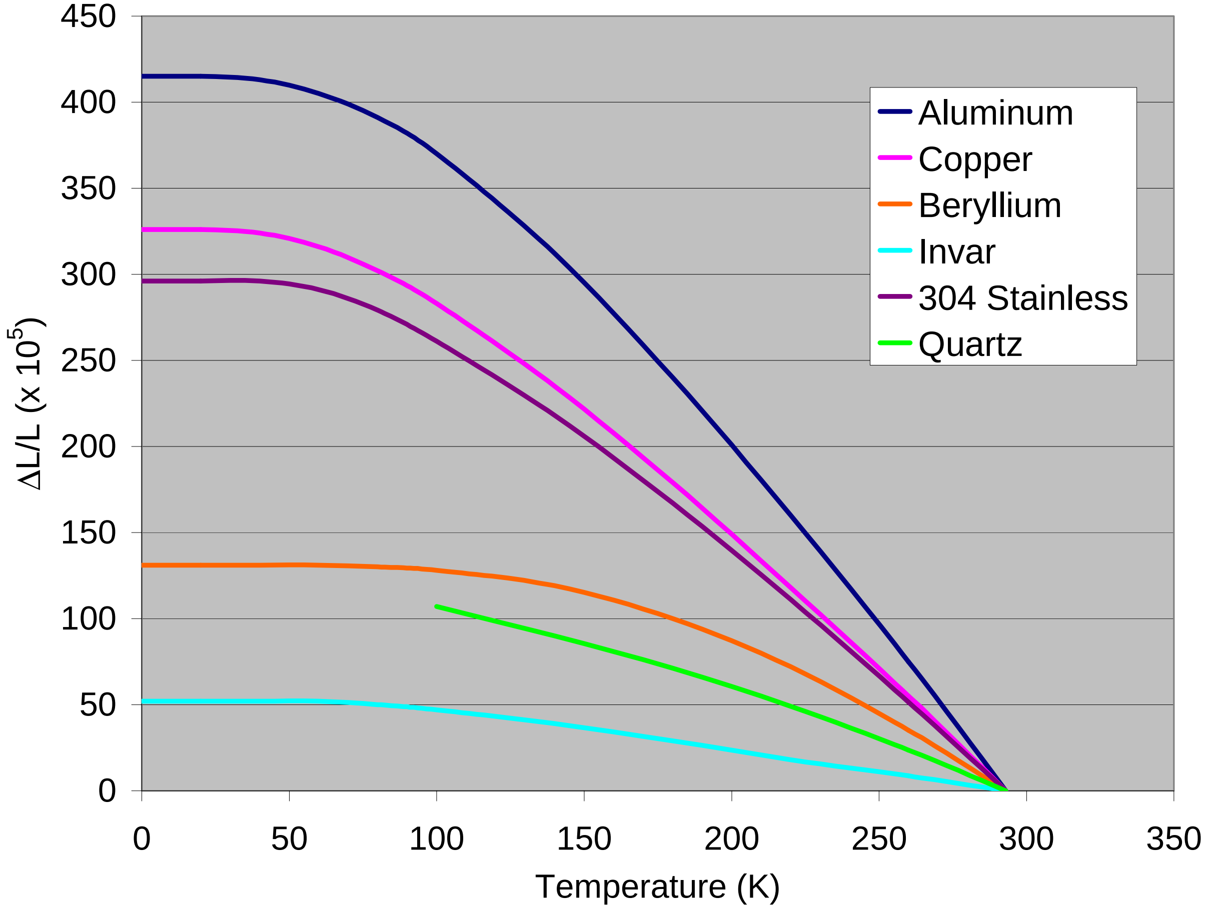
Motor applications

Electromagnetic Performance	*Mechanical Performance*	*Application*	*Requirements*	*Motor Type*
High	**High**	Reaction wheels, control moment Gyros, torque motors, payload pointing	High torque, bandwidth and large motions	Brushless DC, ironless brushless DC
High	**Low**	Low-duty-cycle servomotors (launch vehicles and some payload drives)	High torque and bandwidth, low motion or duty cycle	Brushless DC, ironless brushless DC
Low	**High**	Spin motors for gyros, momentum wheels, scanners	Large range of motion, low torque and bandwidth	Induction, stepper motors or brushless DC
Low	**Low**	Deployment mechanisms, slow drives	Slow or low-duty-cycle motion, low bandwidth	Stepper motors and DC motors (brushed and brushless)

Cryogenic challenges

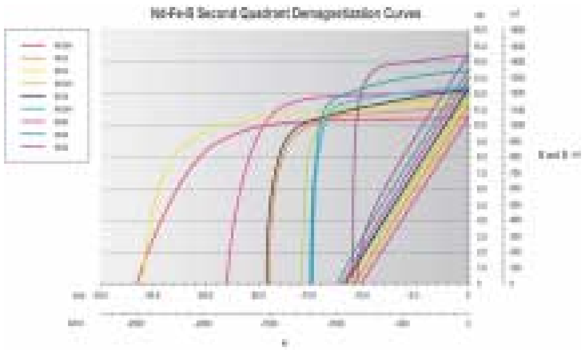
- Thermal contraction
- Magnet materials (ferro- and permanent)
- Bearings & lubrication
- Electrical dissipation

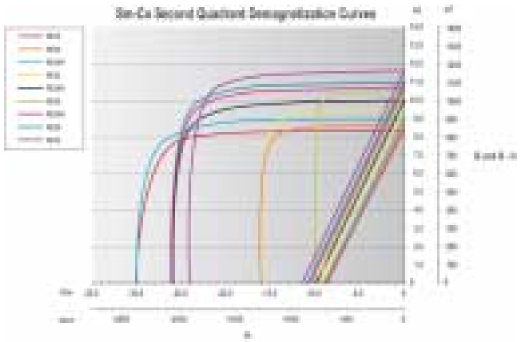
Thermal contraction

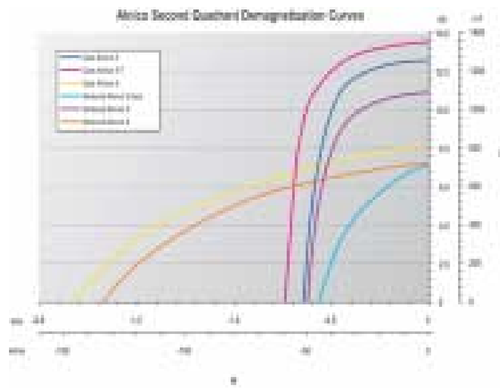


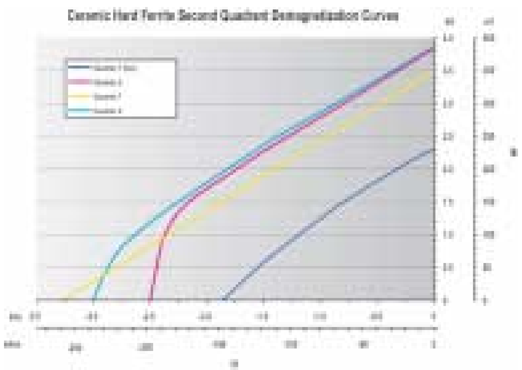
Permanent Magnet Materials

- NdFeB
  - Highest energy product
- SmCo
  - Best suited for cryogenic applications
- AlNiCo
  - inexpensive
- Ceramic
  - Brittle







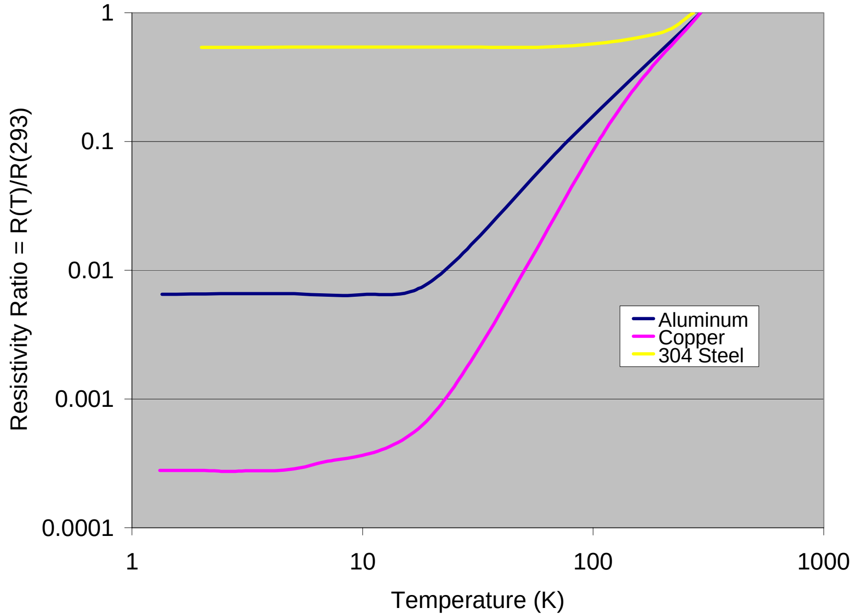


Bearings & Lubrication

- Most bearing failures are due to inadequate lubrication supply rather than base materials
- Hydrocarbon lubricants
  - Freeze out
- Solid (Dry) lubricants
  - TMD
  - Graphite
  - PTFE

Electrical Properties

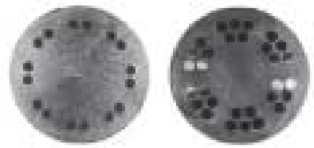
- Electrical resistivity decreases at lower temperatures
- Limited by
  - impurities
  - crystalline defects
  - grain boundaries
- Superconductors

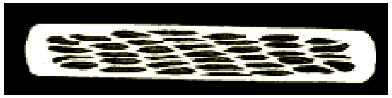


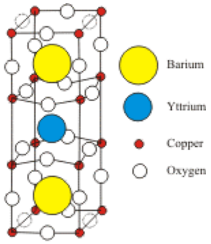
$$\rho\kappa = LT$$

Superconductors

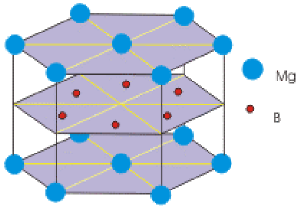
- Metallic
  - NbTi
- Intermetallic
  - Nb_3Sn, Mg_2B
- Ceramic
  - YBCO, BSCCO, TBCCO



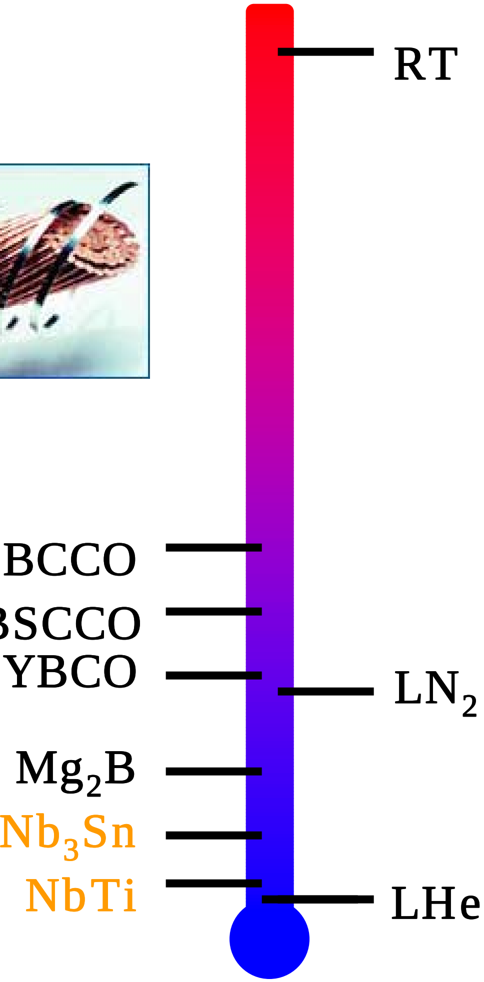




Crystal structure of Y-Ba-Cu-O

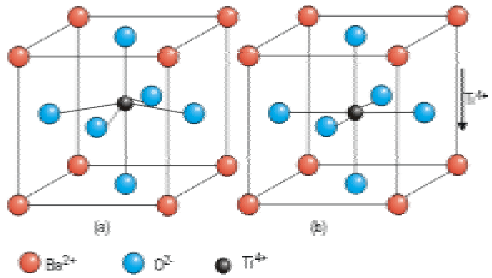


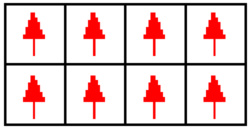
Crystal structure of MgB_2

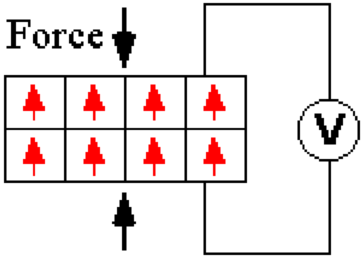


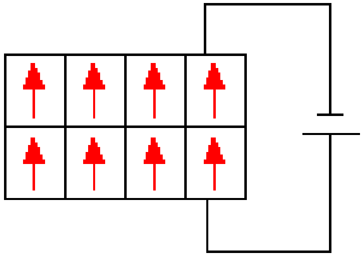
Piezoelectric Materials

- Permanently polarized materials
- Electric field causes distortion of crystal lattice
- Widely used for sensors and actuators

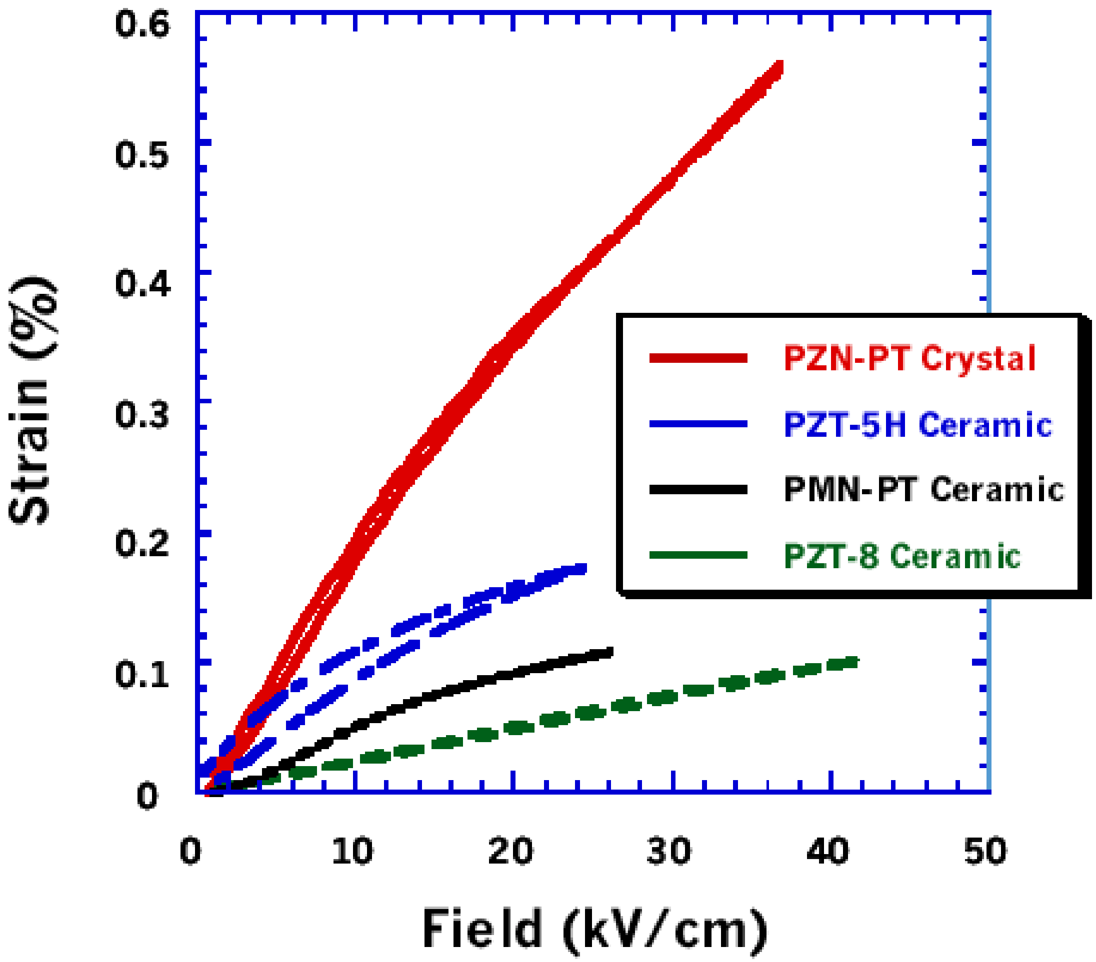






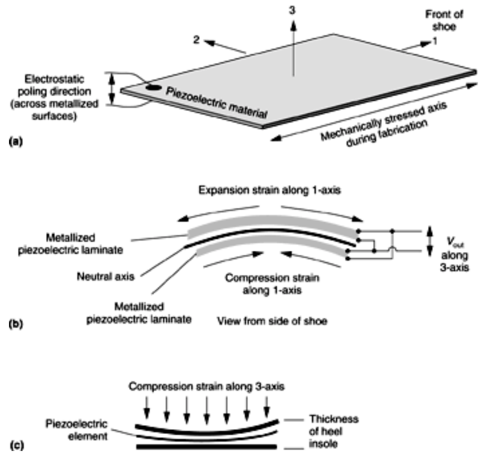


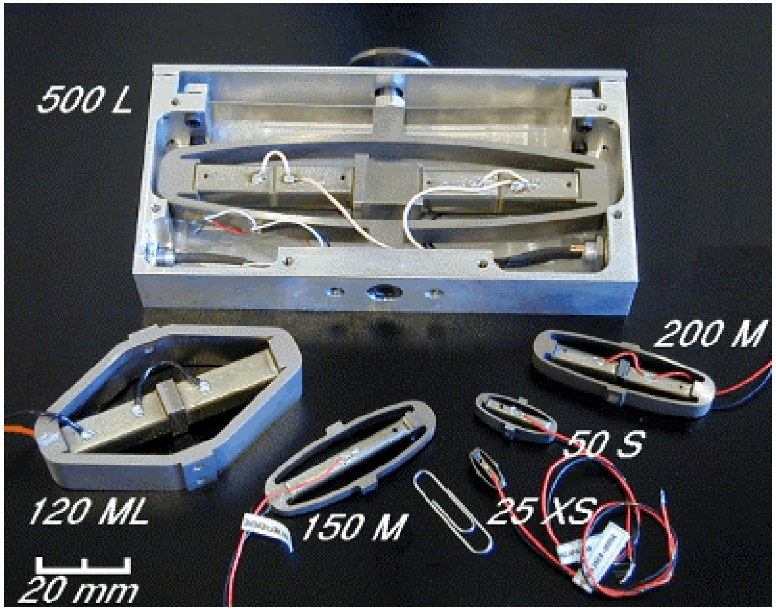
Piezoelectric RT Performance



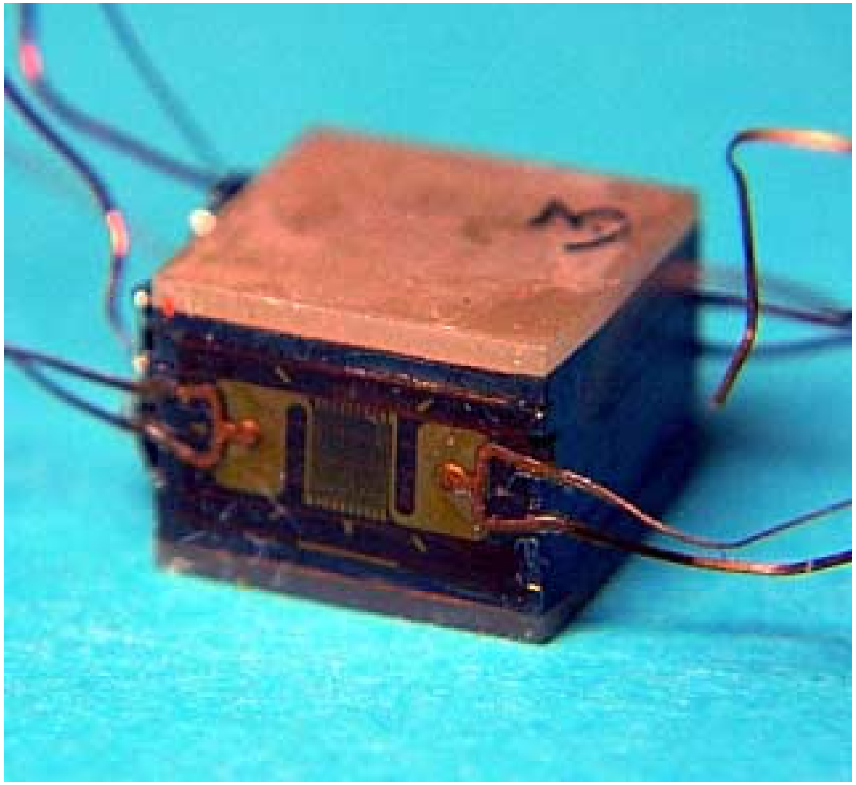
Courtesy of TRS Ceramics

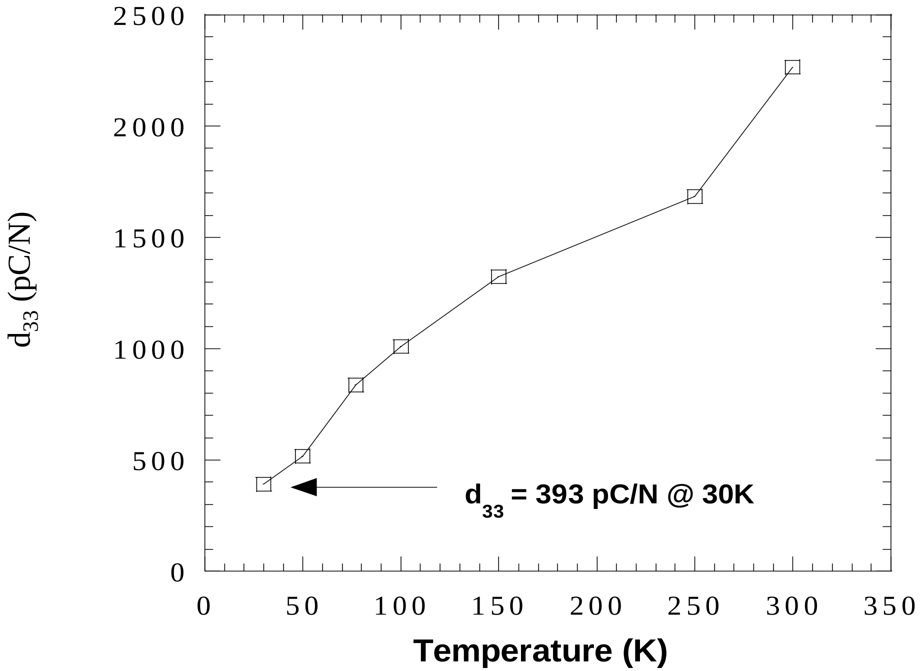
Devices


3
2
1
Front of shoe
Electrostatic poling direction (across metallized surfaces)
Piezoelectric material
Mechanically stressed axis during fabrication
(a)
Expansion strain along 1-axis
Metallized piezoelectric laminate
Neutral axis
Compression strain along 1-axis
Metallized piezoelectric laminate
View from side of shoe
V_{out} along 3-axis
(b)
Compression strain along 3-axis
Piezoelectric element
Thickness of heel insole
(c)


500 L
200 M
50 S
120 ML
150 M
25 XS
20 mm

Cryogenic Performance

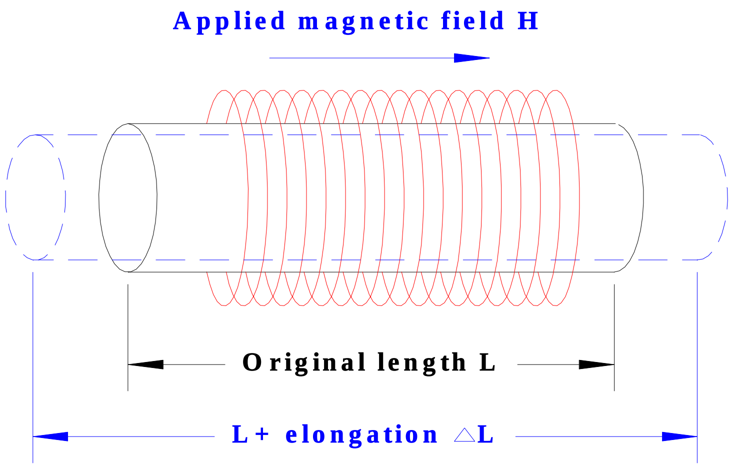




Courtesy of TRS Ceramics

Magnetostrictive Materials

- Elongates in a magnetic field
- Rotation of magnetic domains
- Repeatable
- Reversible



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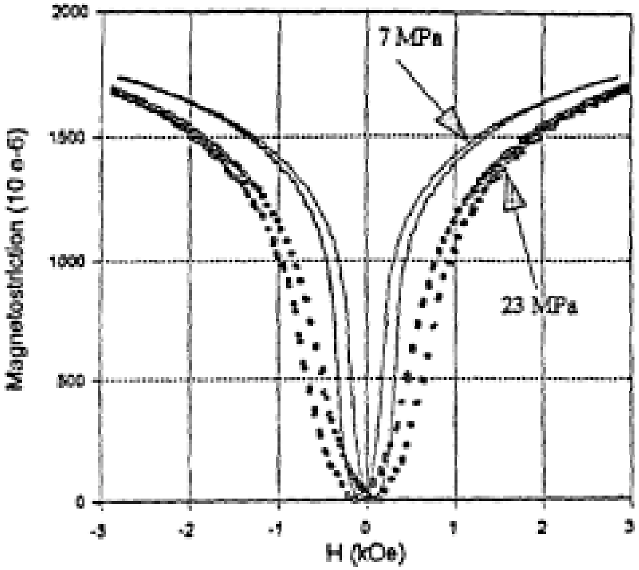
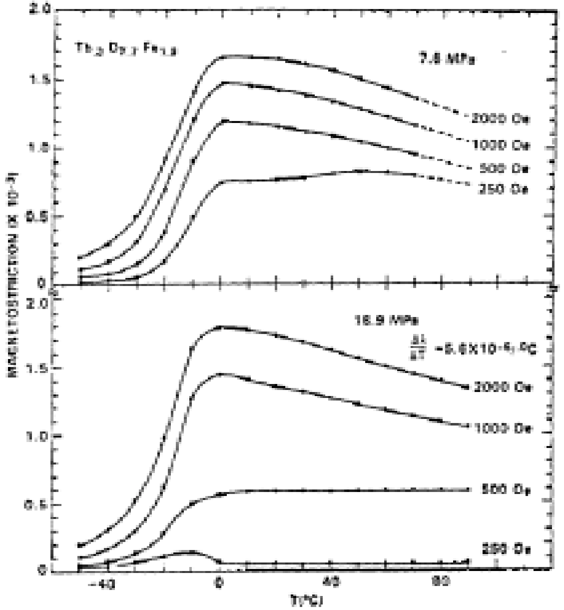
Terfenol-D

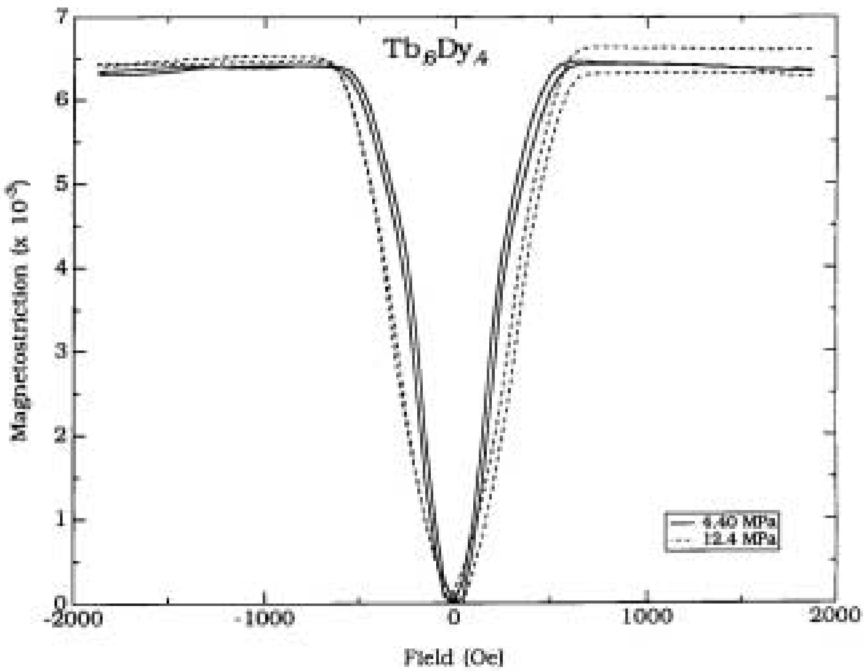
- Discovered at Naval Ordnance Laboratory
- Tb-Dy-Fe alloy
- 1000 – 1700 ppm





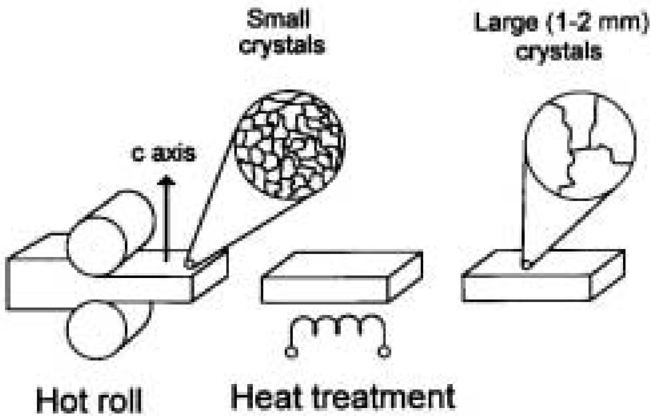
Terbium-Dysprosium

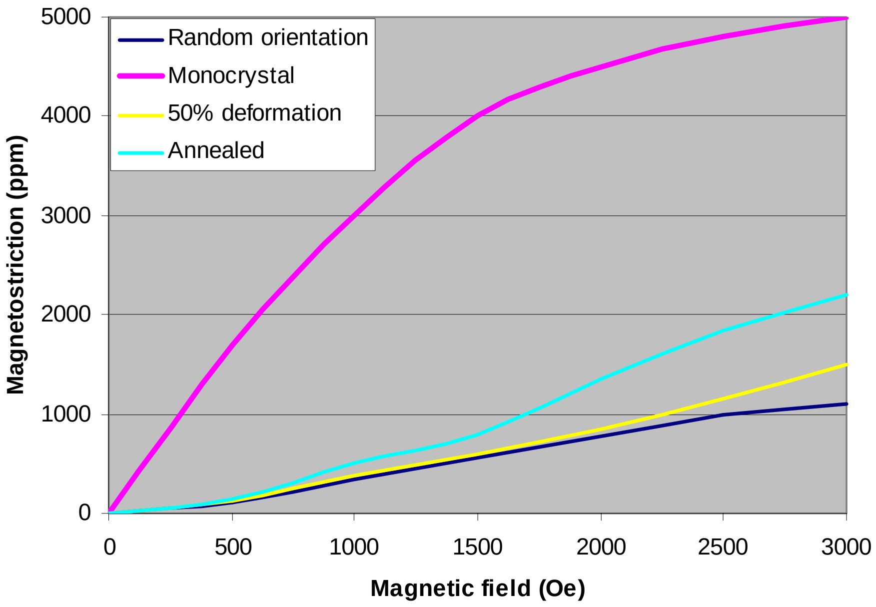
- Highest known magnetostriction: 6300 ppm @ 77 K
- T_c: 150-180 K
- Ductile material
- Fatigue is a problem
- Difficult to grow as signal crystal



Fabrication Techniques

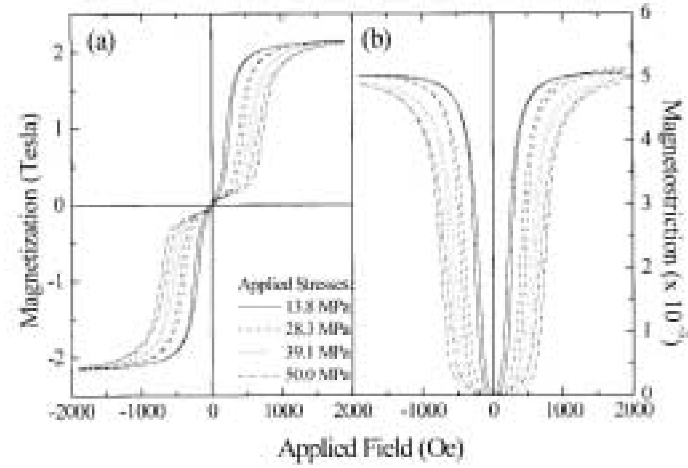
- Polycrystalline TbDy
  - Ellis, Savage (Ames Lab)
  - Fultz, Dooley, Chave (CalTech, JPL)
- Results
  - Stronger material
  - Reduced magnetostriction

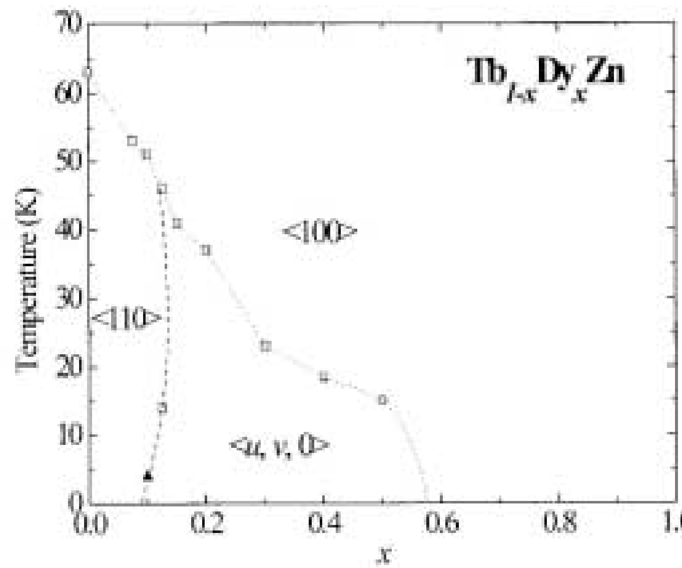




Terbium-Dysprosium-Zinc

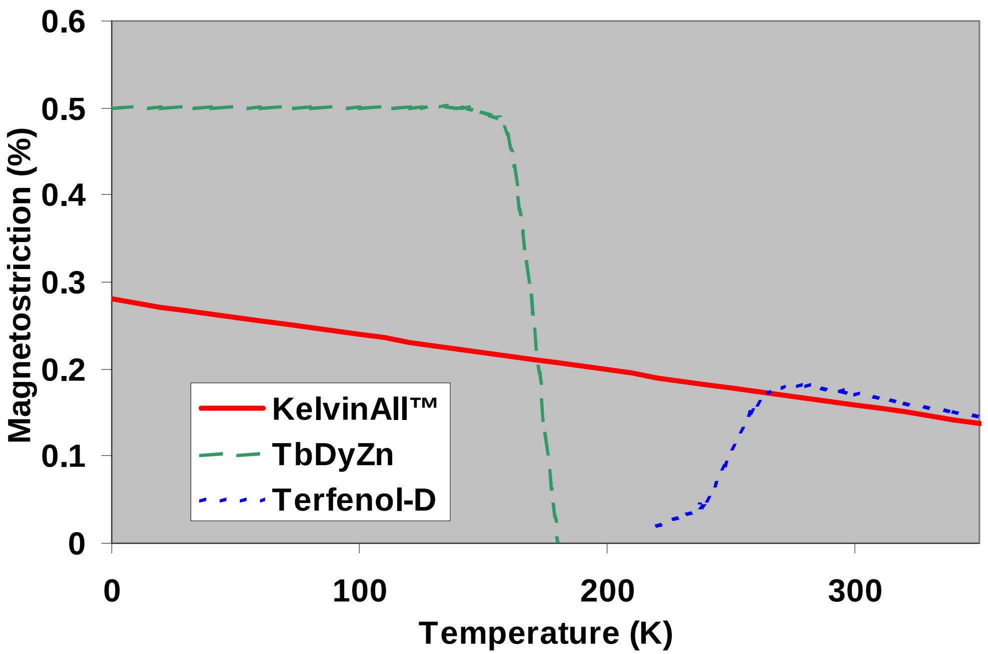
- T_c: 150 K
- Not as ductile as TbDy
- Orientation is critical
- Easier to fabricate
  - Bridgman
  - Oriented growth





KelvinAll®

- Comparable to Terfenol-D at room temperature
- Improved capability at cryogenic temperatures
- Low cost



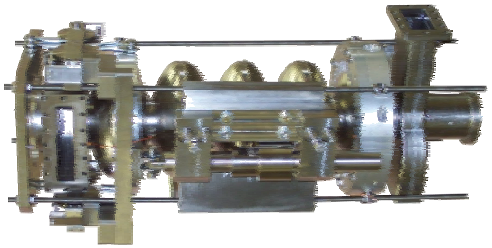
KelvinAll®	**0 - 400 K**	**$1.2X**
TbDyZn	< 150 K	$5-7X
Terfenol	> 250 K	$X

Devices

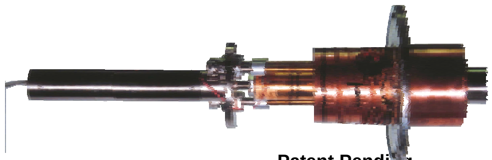
- Linear Actuators
  - Sub-micron positioning resolution
  - High force capability
- Linear Stepper Motors
  - Long range motion
  - Holds position without power
- Controls & Software
  - Manual
  - Automated

Applications

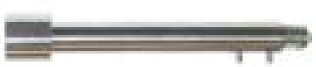
- Active controls for particle accelerators
  - Improves control and reliability
  - Reduces capital costs
- Heat switch for low temperature refrigerator
  - Reduces weight
  - Improves efficiency and reliability
- Metering valve
  - Helium bypass
  - Refrigeration control
  - Variable J-T valve
- Active vibration controls for laser weapons
  - Improves platform stability
  - Increases “hit” rate



Patent Pending



Patent Pending



Patent Pending

Conclusions

- Electromagnetic devices can be adapted for use at cryogenic temperatures
- Smart materials technology is being developed for cryogenic applications

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